

Fluctuations in slope parameter in event-by-event hydrodynamics and momentum anisotropy in heavy ion collisions

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In event by event hydrodynamic model, we have simulated 30-40% Au+Au collisions at RHIC and computed the slope parameter from the invariant pion distribution. In each event, the slope parameter fluctuates azimuthally. Fourier expansion coefficients T_n for the slope parameter and the Fourier expansion coefficients v_n for the azimuthal distribution $\frac{dN}{d\phi}$ are found to be strongly correlated. Strong correlation between the two expansion coefficients suggests that in addition to azimuthal distribution, fluctuations in the slope parameter of the invariant distribution can as well be used to study the final state momentum anisotropy in relativistic energy heavy ion collisions. If measured experimentally, they can serve as additional constraint for hydrodynamical modeling.

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I. INTRODUCTION

In recent years, there is much interest in event-by-event hydrodynamics. Event-by-event hydrodynamics takes into account that in nucleus-nucleus collisions, participant nucleon positions fluctuates from event to event. Effects of such fluctuations are most prominent on the azimuthal distribution of the produced particles. In a non-zero impact parameter collision between two identical nuclei, the collision zone is asymmetric. Multiple collisions transform the initial asymmetry into momentum anisotropy. Momentum anisotropy is best studied by decomposing it in a Fourier series,

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left[1 + 2 \sum_n v_n \cos(n\phi - n\psi_n) \right], n = 1, 2, 3... \quad (1)$$

ϕ is the azimuthal angle of the detected particle and ψ_n is the plane of the symmetry of initial collision zone. In central rapidity region, for smooth initial matter distribution (obtained from geometric overlap of density distributions of the colliding nuclei), plane of symmetry of the collision zone coincides with the reaction plane (the plane containing the impact parameter and the beam axis), $\psi_n \equiv \Psi_{RP}, \forall n$. The odd Fourier coefficients are zero by symmetry. However, fluctuations in the positions of the participating nucleons can lead to non-smooth density distribution, which will fluctuate on event-by-event basis. The participating nucleons then determine the symmetry plane (ψ_{PP}), which fluctuate around the reaction plane [1]. As a result odd harmonics $v_1, v_3, v_5 \dots$, which in central rapidity region are exactly zero for smoothed initial distribution, can be developed. In RHIC and LHC energy collisions, odd harmonics has indeed been measured in experiments [2][3][4][5]. Explicit event-by-event hydrodynamic simulations of relativistic heavy ion collisions

also results in odd harmonics [6] [7][8][9] [10][11][13][14] [28][15] [16][17].

While momentum anisotropy is best studied by Fourier expansion of the azimuthal distribution, in the present paper we explore the possibility of using another observable, namely the slope parameter of the transverse momentum distribution for the produced particles. In experiments azimuthal angle integrated transverse momentum distribution ($\frac{d^2N}{dy_{PT}d\phi}$) of produced particles are routinely measured. Angle integrated momentum distribution is of exponential nature. Slope (T) of the distribution can be interpreted approximately as the temperature of the fireball produced in the collisions. In event-by-event hydrodynamics the initial medium is granular and even in central collisions have azimuthal dependence. As a consequence the freeze-out surface can have azimuthal dependence. The invariant particle spectra will depend on the azimuthal angle. Hydrodynamic simulations indicate that the invariant spectra ($\frac{d^2N}{dy_{PT}d\phi}$) remains exponential even as a function of the azimuth. Asymmetry in the momentum distribution then be reflected as the azimuth dependent slope parameter ($T(\phi)$). Experimental measurements can be easily extended to study of azimuthal fluctuations in the slope parameter. The data can serve as additional constraint for hydrodynamical modeling.

In the present paper, in event-by-event hydrodynamics, we have simulated $\sqrt{s_{NN}}=200$ GeV 30-40% Au+Au collisions and studied azimuthal fluctuations of the slope parameter. When averaged over many events, azimuthal fluctuation in the slope parameter is very similar to that of azimuthal distribution; though less pronounced. In a single event however, the slope parameter appears to fluctuates more strongly over the azimuth than the azimuthal distribution. In analogy to the Fourier expansion of the azimuthal distribution $\frac{dN}{d\phi}$, we have Fourier expanded azimuth dependent slope parameter. The expansion coefficients of the slope parameter and that of azimuthal distribution appear to be strongly correlated. Strong correlations between two expansions coefficients

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suggest that like the azimuthal distributions, azimuth dependent slope parameter can be used to characterise the momentum anisotropy.

The paper is organised as follows: in section II the hydrodynamic model used presently is briefly discussed. In section III simulation results are discussed and finally in section IV conclusions are drawn.

II. HYDRODYNAMIC MODEL

In event-by-event hydrodynamics, one generally solves for the energy-momentum and baryon number conservation equations,

$$\partial_\mu T^{\mu\nu} = 0, \quad (2)$$

$$\partial_\mu J^\mu = 0 \quad (3)$$

where $T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - Pg^{\mu\nu}$ is the energy-momentum tensor and $J^\mu = n_B u^\mu$ is the particle 4-current. ε , p , n_B and u are energy density, pressure, net baryon density and hydrodynamic 4-velocity respectively. $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the metric tensor. Presently we assume that fluid is baryon free and disregard Eq.3. We also disregard any dissipative effect. Assuming boost invariance we solve the equations with the code AZHYDRO-KOLKATA [18] in $(\tau = \sqrt{t^2 - z^2}, x, y, \eta_s = \frac{1}{2} \ln \frac{t+z}{t-z})$ coordinate system. Hydrodynamics equations (Eq.1) are closed with an equation of state (EoS) $p = p(\varepsilon)$. Presently, we use an equation of state where the Wuppertal-Budapest [19, 20] lattice simulations for the deconfined phase is smoothly joined at $T = T_c = 174$ MeV, with hadronic resonance gas EoS comprising of all the resonances below mass $m_{res}=2.5$ GeV. Details of the EoS can be found in [21].

Solution of hydrodynamic equations requires to specify the fluid energy density distribution $\varepsilon(x, y)$, velocity distribution $v_x(x, y), v_y(x, y)$ at the initial time. A freeze-out prescription is also needed to convert the information about fluid energy density and velocity to invariant particle distribution. We assume that at the initial time $\tau_i=0.6$ fm initial fluid velocity is zero, $v_x(x, y) = v_y(x, y) = 0$. The freeze-out temperature is fixed at $T_F=130$ MeV. For the initial energy density distribution we resort to Monte-Carlo Glauber model. Details of the Monte-Carlo Glauber model can be found in [22]. In a Monte-Carlo Glauber model, according to the density distribution of the colliding nuclei, two nucleons are randomly chosen. They are assumed to interact if the transverse separation is below $\sqrt{\frac{\sigma_{NN}}{\pi}}$. For RHIC energy collisions $\sigma_{NN} \approx 42mb$, a value used in the present simulations. Transverse position of the participating nucleons (which are known in each event) will fluctuate from event-to-event. If a particular event has N_{part} participants, participants positions in the transverse plane can be labeled as, $(x_1, y_1), (x_2, y_2) \dots (x_{N_{part}}, y_{N_{part}})$. Energy density distribution in the particular event can be ob-

tained by assuming that each participant deposits energy ε_0 in the transverse plane,

$$\varepsilon(x, y) \approx \varepsilon_0 \sum_{i=1}^{N_{part}} \delta(x - x_i, y - y_i) \quad (4)$$

For use in fluid dynamical models, the discrete density distribution is smoothed by smearing the participant positions by a Gaussian function,

$$\varepsilon(x, y) = \varepsilon_0 \sum_{i=1}^{N_{part}} g_{Gauss}(x - x_i, y - y_i, \sigma) \quad (5)$$

$$g_{Gauss}(x - x_i, y - y_i, \sigma) \propto e^{-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma^2}}, \quad (6)$$

In [23][24], influence of the Gaussian width i.e. the smoothing parameter σ , on flow coefficients were studied in Au+Au collisions. Elliptic and triangular flows are minimally influenced by the smoothing parameter σ . Higher flow coefficients, however are influenced by the choices of σ . Presently, we have used $\sigma=0.25$ fm.

III. RESULTS

A. Feasibility of slope parameter as a probe for momentum asymmetry

Let us first demonstrate the feasibility of slope parameter in characterising momentum anisotropy of final state particles. We have simulated 30-40% Au+Au collision at RHIC energy, with two initial condition IC-1 and IC-2. IC-1 is a randomly chosen MC Glauber model initial condition and IC-2 is the initial condition obtained by averaging over average of 500 MC events. In Fig.1a and (b), energy density distributions for the two initial conditions are shown. When averaged over large number of events, the initial condition is rather smooth as it is in smooth hydrodynamics (obtained from optical Glauber model calculations). Initial condition IC-1, corresponding to a single MC event clearly shows granular structures.

In Fig.1c and d, angular dependence of π^- spectra from the evolution of initial distributions IC-1 and IC-2 are shown. Spectra are shown for azimuthal angle $\phi=0, 1.26, 2.51, 3.77, 5.03$ and 6.28 respectively. In the inset of 1c and d, spectra are shown in a limited p_T range. For IC-2, as expected, the spectra do not show any angular dependence. The angular dependence however is manifestly presented in IC-1. We also note that at any angle the spectrum is of exponential nature, $\exp(-m_T/T)$. Azimuth dependent slope parameter then can be used to probe momentum anisotropy of the final state particles. In smooth hydrodynamics, the azimuth independent slope parameter can be interpreted as effective temperature of a single fireball emitting particles. Azimuth

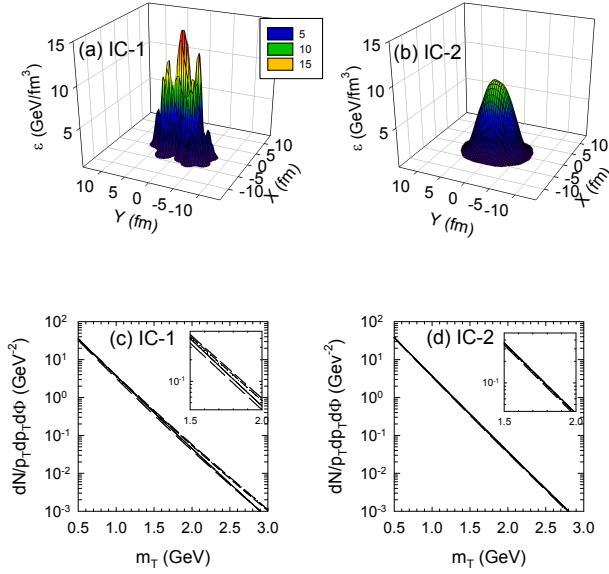


FIG. 1: (color online) (a) Distribution of initial energy density in a single MC event (IC-1), (b) distribution of energy density averaged over 500 MC events (IC-2). (c) Transverse momentum distribution for π^- from hydrodynamic simulation of initial condition IC-1, (d) Transverse momentum distribution for π^- from hydrodynamic simulation of initial condition IC-2.

dependent slope parameter then can be interpreted as the temperatures of multiple sources.

B. Azimuthal variation of slope parameter in Event-by-event hydrodynamics

For 500 MC Glauber events we have simulated π^- production in 30-40% Au+Au collisions at RHIC. For each event we find the slope parameter ($T(\phi)$) between $p_T=1-2$ GeV, and compute the fluctuations in $T(\phi)$ as,

$$\Delta T(\phi) = \frac{T(\phi) - \overline{T}}{\overline{T}}; \quad \overline{T} = \frac{\int_0^\infty d\phi T(\phi)}{2\pi} \quad (7)$$

In simulations we also have calculated the azimuthal distribution $\frac{dN}{d\phi}$ in each of the event. Fluctuations in azimuthal distribution are calculated in a similar way,

$$\Delta N(\phi) = \frac{\frac{dN}{d\phi} - \overline{\frac{dN}{d\phi}}}{\overline{\frac{dN}{d\phi}}}; \quad \overline{\frac{dN}{d\phi}} = \frac{\int_0^\infty d\phi \frac{dN}{d\phi}}{2\pi} \quad (8)$$

In Fig.2 azimuthal fluctuations $\Delta T(\phi)$ and $\Delta N(\phi)$ are shown. In Fig.2a, the circles with error bars shows the azimuthal variation for the event averaged fluctuations $\langle \Delta T(\phi) \rangle$. When averaged over all the events, the slope parameter does not show rapid variation with azimuth. However, large error bars do indicate that at any azimuth, event-by-event variations are rather large. In

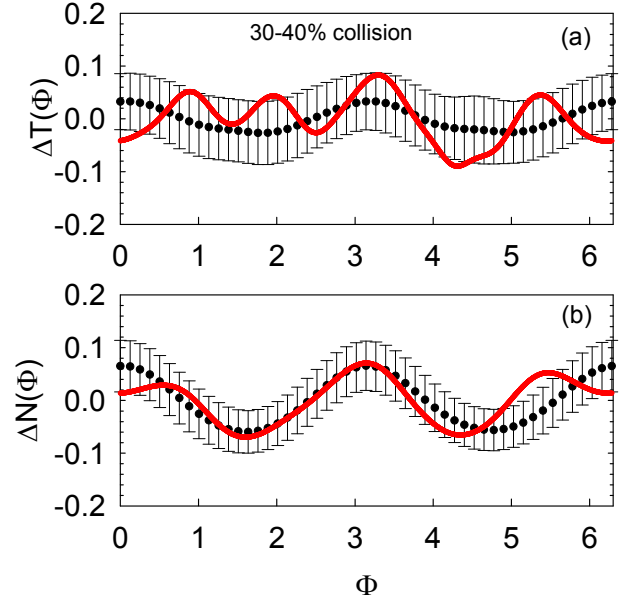


FIG. 2: (color online) (a) Variation of the fluctuations in the slope parameter $\Delta T(\phi)$ with azimuth. The red line is for a single MC Glauber event and the filled circles with error bars are for average of 500 MC Glauber events. (b) same as in (a) but for fluctuations in the azimuthal distribution ΔN .

Fig.2a, the red line is the fluctuations in the event IC-1. $T(\phi)$ more oscillates more rapidly than the event averaged value. Fig.2b shows the azimuthal variation $\Delta N(\phi)$. Event averaged $\langle \Delta N \rangle$ fluctuations are similar to that of the slope parameter, though more pronounced. In Fig.2b, the red line indicate azimuthal variation of ΔN in the event IC-1. In a single event, unlike ΔT , ΔN oscillates less rapidly.

C. Fourier expansion of slope parameter

As in Eq.1, azimuthal anisotropy of slope parameter can be studied by Fourier expansion,

$$T(\phi) = T_0 \left[1 + 2 \sum_n T_n \cos(n\phi - n\psi_n) \right], \quad n = 1, 2, 3... \quad (9)$$

where the expansion coefficients are labeled as T_1, T_2, \dots etc. In Eq.9 (also in Eq.1) ψ_n is the participant plane angle. In event-by-event hydrodynamics, one generally characterise the asymmetry of the initial collision zone in terms of various moments of the eccentricity (ϵ_n) [25],[26],[27],

$$\epsilon_n e^{in\psi_n} = - \frac{\int \int \epsilon(x, y) r^n e^{in\phi} dx dy}{\int \int \epsilon(x, y) r^n dx dy}, \quad n = 1, 2, 3.. \quad (10)$$

which also determine the participant plane angle ψ_n .

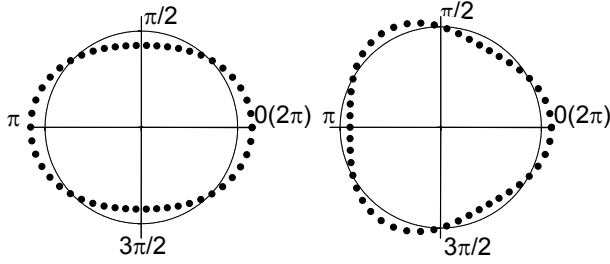


FIG. 3: (Color online) Pictorial depiction of particle distribution with finite v_2 and v_3 in the transverse plane. The red lines in the left and right panels show the polar plot of the azimuthal distribution $\frac{dN}{d\phi}$ with finite v_2 and finite v_3 . The black circles shows the distribution when $v_2=v_3=0$.

To understand the implications of the coefficients T_n , let us remember that the physical implications of the flow coefficients v_n in Eq.1. In Fig.3 schematic diagram of the azimuthal distribution $\frac{dN}{d\phi}$ with finite v_2 and with finite v_3 are shown in polar coordinates. For finite v_2 , in the transverse plane, the distribution is elliptical, particles are preferentially produced at $\phi = 0$ and $\phi = \pi$. The same for distribution with finite v_3 however is triangular in shape. Preferential emission occurs in three direction, $\phi=0, 2\pi/3$ and $4\pi/3$. In Fig.3 solid circles shows the azimuthally symmetric distribution when v_2 or v_3 are zero. Microscopically, due to multiple collisions, initial asymmetry in spatial density distribution gets converted into asymmetry in the momentum space distribution. If it is assumed that particles are emitted from a hot fireball in the momentum space, then for finite v_2 (v_3), momentum space density distribution of the fireball, in the transverse plane is elliptical (triangular). The coefficients v_n in Eq.1 are called flow coefficients as they indicate preferential flow of particles in certain directions. Physical implication of the coefficients T_n in Fourier expansion of the slope parameter is similar to that of the flow coefficients v_n . In a distribution with finite T_2 , in the transverse plane fireball temperature is not uniform rather elliptical in shape, more along $\phi=0$ and π and less in other directions. Similarly fireball temperature will be of triangular shape in distribution with finite T_3 . In a fireball picture such angular dependence implies that a number of fireballs participate in particle production. Considering the similarity with flow coefficients v_n , in the following T_n will be called temperature flow coefficients. Similar to flow coefficients, microscopic origin of temperature flow coefficients is also the asymmetry in the initial (spatial) density distribution.

In a hydrodynamic model flow coefficients v_n are response of the initial (spatial) asymmetry of the medium produced in the collisions. They are expected to be strongly correlated with initial eccentricity measured ϵ_n . Indeed, in smooth hydrodynamics elliptic flow is strongly correlated with initial eccentricity ϵ_2 . In event-by-event

hydrodynamics correlation between flow coefficient v_n , with initial eccentricity measures ϵ_n has been studied previously [16],[17],[28],[29]. It was shown that in event-by-event hydrodynamics, elliptic flow is strongly correlated with initial eccentricity. Comparatively weak correlation was observed between triangular flow and initial triangularity. Correlation between higher flow coefficients and asymmetry measures gets even weaker. De-correlation of higher order flows could be understood as due to nonlinear mixing of modes [16]. For example, Gardim et al [16] showed that in order to correctly predict v_4 and v_5 , one must take into account nonlinear terms proportional ϵ^2 and $\epsilon_2\epsilon_3$ respectively.

TABLE I: Correlation measure for (i) flow harmonics (v_n) and eccentricity (ϵ_n), (ii) temperature flow coefficients (T_n) and eccentricity (ϵ_n), and (iii) between temperature flow coefficients (T_n) and flow coefficient (v_n).

	$C_{measure}$				
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
(v_n, ϵ_n)	0.656	0.974	0.846	0.682	0.715
(T_n, ϵ_n)	0.572	0.797	0.796	0.651	0.651
(T_n, v_n)	0.897	0.824	0.940	0.926	0.909

As we have argued here, temperature flow coefficients T_n are also responses of the initial (spatial) asymmetry of the system. How they are correlated with initial eccentricity measures is an interesting study. In Fig.4, we have studied the correlation between initial eccentricity (ϵ_n) and temperature flow coefficients (T_n). For each of the 500 MC-Glauber events the slope parameter $T(\phi)$ was Fourier expanded to find out the temperature flow coefficients T_n , $n=1,2,\dots,5$. In the left panel of Fig.4, for the 500 events, the temperature flow coefficients T_n ($n=1,2,\dots,5$) are plotted against initial eccentricity measure ϵ_n . For a perfect correlation $T_n \propto \epsilon_n$ and all the events should lie on a straight line. It is evident from our simulations that temperature flow coefficients are weakly correlated with initial eccentricity measures.

The result is not a complete surprise. From our previous studies, we know that with the exception of elliptic flow v_2 , the flow coefficient v_n are also weakly correlated with initial eccentricity measures. It is evident from the middle panel of Fig.4 where we have plotted the flow coefficients v_n against the eccentricity measures ϵ_n . As expected, only v_2 appears to be strongly correlated with ϵ_2 . Other flow coefficients are weakly correlated with eccentricity measures. In the right panel of Fig.4, we have plotted temperature flow coefficients T_n against the flow coefficient v_n . Interestingly, temperature flow coefficients T_n and flow coefficient v_n appear to be strongly correlated.

In [30][31] a quantitative measure was defined to quantify the correlation between flow coefficients and initial spatial asymmetry measure.

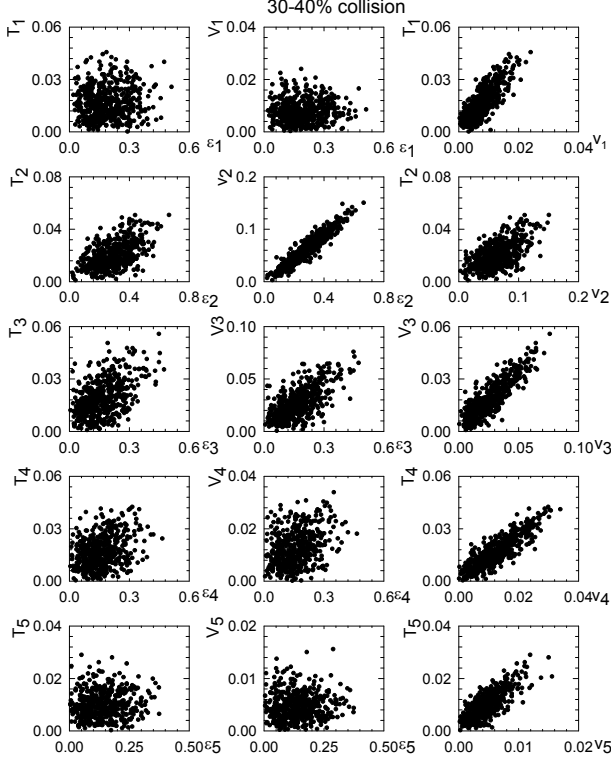


FIG. 4: Each dot in the plots represent event-by-event hydrodynamic simulation for flow coefficients v_n , temperature flow coefficients T_n . Left panel: Correlation between temperature flow coefficients T_n with initial eccentricity measure ϵ_n . Middle panel: Correlation between flow coefficients v_n with initial eccentricity measure ϵ_n . Right panel: Correlation between temperature flow coefficients T_n with flow coefficients v_n .

$$C_{measure}(n) = 1 - \frac{\sum_i [v_n^i(\epsilon_n) - v_{n,st.line}(\epsilon_n)]^2}{\sum_i [v_{random}^i(\epsilon) - v_{st.line}(\epsilon)]^2} \quad (11)$$

$C_{measure}$ essentially measures the dispersion of the simulated flow coefficients from the best fitted straight line, relative to completely random flow coefficients. It varies between 0 and 1. If flow coefficients are perfectly correlated then $v_n \propto \epsilon_n$ and $C_{measure}$ is identically unity. For completely random flow coefficients, $C_{measure}=0$. To obtain an even ground for comparison of $C_{measure}$ for different flow coefficients, the flow coefficients (v_n) and the asymmetry parameters (ϵ_n) are scaled to vary between 0 and 1. A similar equation can be used to quantify the correlation between temperature flow coefficients T_n and initial asymmetry measure ϵ_n or between temperature flow coefficients T_n and flow coefficients v_n . In table.I,

we have listed the $C_{measure}$ values for correlation between v_n and ϵ_n , between T_n and ϵ_n and between T_n and v_n . Quantitatively compared to flow coefficients v_n , temperature flow coefficients T_n are less correlated with ϵ_n . The difference is most prominent for second harmonic $n=2$ and lessened in higher order harmonics. $C_{measure}$ values also indicate that the correlation between temperature flow coefficients T_n and flow coefficient v_n are rather high for all n . T_n and v_n are much better correlated than the correlation between v_n and ϵ_n or between T_n and ϵ_n .

Event-by-event hydrodynamic simulation result that the temperature flow coefficients T_n and flow coefficients v_n are rather strongly correlated strongly suggests that apart from the azimuthal distribution $\frac{dN}{d\phi}$, the azimuthal fluctuations in the slope parameter of invariant spectra can as well be used to study final state momentum anisotropy. The fluctuations can be measured experimentally and can serve as additional constraints for hydrodynamic modeling.

IV. SUMMARY AND CONCLUSIONS

In event-by-event hydrodynamical model for heavy ion collisions, due to fluctuations in participant positions, the initial conditions fluctuates event-by-event. These fluctuations are manifested as momentum anisotropy in the final particle distribution and in general are studied by Fourier expanding the azimuthal distribution, the expansion coefficients characterising the momentum anisotropy. By explicit event-by-event hydrodynamic simulation we have shown that in event-by-event hydrodynamics, the slope parameter of the invariant distribution will also fluctuates with azimuth and can as well be used to study the momentum anisotropy. For 500 MC Glauber events, we have simulated Au+Au collisions at RHIC and from the invariant pion spectra computed the azimuthal distribution $\frac{dN}{d\phi}$ and from an exponential fit to the spectra between $p_T=1-2$ GeV, also the slope parameter $T(\phi)$. $\frac{dN}{d\phi}$ and $T(\phi)$ were Fourier expanded and studied its correlation between expansion coefficients and initial eccentricity measures. With the exception of $n=2$, expansion coefficients v_n for the azimuthal distribution $\frac{dN}{d\phi}$ are weakly correlated with the initial eccentricity measures ϵ_n . Without any exception, the expansion coefficients T_n for the slope parameter are also weakly correlated with the initial eccentricity measures ϵ_n . The coefficients v_n and T_n are however strongly correlated. Strong correlation between v_n and T_n suggest that they complement each other. If measured experimentally fluctuations in slope parameter can be used to study momentum anisotropy and can serve as additional constraint for hydrodynamical modeling.

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